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THE INTERRELATIONSHIP OF FACTORS AFFECTING ROAD CAPACITY

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Military cargo trucks operate in convoys when pushing supplies forward on a road, not in a steady stream of trucks, but in groups of trucks separated by specified intervals, operating at speeds and leads determined partly by the characteristics of the road and partly by convoy doctrine. When thinking of the real capacity of a road, then, we should think in terms of a transportation system that moves according to certain rules and physical limitations. We should also be aware of the fact that roads are seldom used to full capacity because of limitations in the number of trucks available, maintenance resources, and hours of operation .

BASIC RELATIONSHIPS

The average speed and lead maintained over a period of operation are basically what determine capacity. The length of the route determines the number of trucks needed to fill the system; also, payload and operating period enter into capacity calculations, but these are secondary and more manageable variables. The main problem is to estimate speed and lead for a variety of conditions. These basic relationships are illustrated in Chart 1. Note that the ratio of speed to lead is important because it yields the truck rate, or trucks forward per hour. Given truck rate, distance, payload, and operating period, one can then compute the supply rate in tons forward per day.

These basic relationships also apply to one-way roads but we have to allow for two factors which reduce the forward throughput: (1) road

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time needed for returning empty trucks; (2) road time needed for clearing off convoys so that the flow direction can be reversed. We found that throughput can be increased by dividing a one-way road into shuttle segments as in Chart 2. The supply rate is proportional to the number of trucks operating on each segment multiplied by the number of round trips per truck per operating period. Supply rate is again proportional to the ratio of speed to lead, but the time available for moving supplies forward and for returning empty trucks (hours per round trip) is reduced by the amount of time per round trip required for convoy clearance.

The interaction of these two terms gives flexibility in the way in which one-way roads can be used. In general, more supplies can be pushed through by using short segments, but at a heavy penalty in the number of trucks required. The next two charts illustrate the effect on road capacity of varying operating period and segment length; also, the effect of speed. Both charts are for a one-way road 1000 km in length and a payload of 4 tons. Lead was arbitrarily held constant at 100 meters so that the separate effect of speed could be shown. In chart 3 we have divided the 1000 km into 20 segments of 50 km each and we see that operating period has a drastic effect; in fact, at low speeds it is necessary to operate for 12 hours or more in order to push any cargo through. Also, the higher the speed, the more sensitive the supply rate is to operating period. Note the one point circled on the 20 kph line, at around 5000 tons per day. This point also appears on chart 4, which shows the effect of varying segment length for a maximum operating period of 20 hours per day. We were already using fairly short segments so our sample point is well up on the 20 kph line. Had we doubled the segment length (from 50 to 100 km) we would have cut our supply rate in half in this case.

FACTORS AFFECTING ROAD CAPACITY

Now let's look at the factors involved (Chart 5). I have listed 19 factors that affect road capacity or truck requirements in one way or another. Note that I keep truck requirements in mind because I think we should understand how to estimate throughput when there are

not enough trucks to use a road to capacity. Most of these factors are self-explanatory; the term, "moisture", however, needs some explanation. This is an arbitrary term to cover season, weather, drainage, or to explain that a road surface or subsurface is dry, moist, wet, or has a specified moisture content.

It would be ideal for computing road capacity if we had a table of speeds and leads for all possible combinations of relevant factors (not all of the factors in Chart 5 affect speed or lead). The problem is, even for selected factors as indicated there is a huge number of combinations. If we accounted for four surface types, three condition categories, and so on as shown on the chart, we would end up with 29,160 combinations. However, let's put that problem aside for a moment and go on to consider some of the interrelationships.

Chart 6 lists the same 19 factors. The right-hand side of the chart is a matrix of all 19 factors showing that one can conceive of relationships in at least 89 out of a possible 180 boxes in the matrix, as shown by the dots. I won't go into all of these but I'll mention a few. Roadway maintenance, for example, seems to be related to almost everything else, although the type of relationship varies. Obviously the amount of maintenance required will depend on surface type, base thickness, subsoil, and road condition. The relationship with width is more complicated: a wide road requires more effort and material than a narrow road; on a narrow road the hours available for maintenance might have to be scheduled in accordance with operational needs and equipment and materials might be stockpiled differently than on a wide road. Similarly for shoulder width, with the addition that wide shoulders facilitate stockpiling of equipment and materials. As terrain becomes more difficult, maintenance problems increase; for example, sources of material are probably farther away. The effect of moisture is clear ... road repair stops when equipment is mired down. The relationship with convoy doctrine is more tenuous, although there could be speed limits in sections under maintenance. There is a more definite relationship with truck type; heavy trucks may be harder on roads, depending on wheel loadings and footprint area and

large trucks may suffer more from the interference effects of road maintenance. Gross weight has somewhat the same effect. Operating period raises the problem of scheduling truck movements and road maintenance. "Day vs. night" operations change the interference effect; "empty vs. loaded" brings us back to weight and mobility effects. Truck maintenance problems would increase on a road not properly maintained. Other traffic aggravates the interference of road maintenance.

It would be extremely difficult to establish all of these relationships with precision and build them into a method for estimating road capacity. We must move in the direction of simplicity, and the first step toward this is shown on the left-hand side of Chart 6.

Here we see relationships between the 19 factors and five variables: speed, lead, truck rate, supply rate, and number of trucks. The relationships are indicated by dots; those in squares were included in the RAND method. Again this is too detailed to cover item by item so we'll look at several examples. Surface type could affect all five variables, as could condition and terrain. To keep the RAND method simple, however, we let speed vary with surface type, condition, and terrain, but we adhered to the speedometer multiplier concept so that only surface type had an effect on truck rate.* Convoy doctrine also affects all five variables and can be a major determinant of road capacity as we shall see in a moment. This raises a semantic difficulty ... one can argue that the capacity of a road has nothing to do with doctrine. Again we must remember that we are talking about controlled military truck operations and that without control, a long stream of trucks would have many problems; therefore, doctrine and road characteristics are inextricably bound together, along with the availability of trucks and maintenance resources.

Thus far we have considered hypothetical roads, assuming that a road with a fixed set of characteristics runs from point A to point B, and we have been concerned with the problem of too many combinations

* This was partly due to the added effect of dust on the ratio of speed to lead.

and too many relationships. This is further complicated by the fact that some roads vary almost by the kilometer, especially in parts of Southeast Asia. Look at Chart 7, for example. This was one of our test routes in Thailand and was part of the main route between Khorat and Sara Buri before the Friendship Highway was built. Over this distance of 131 km we identified no less than 20 "segments," that is, sections with fairly uniform characteristics. According to the way we categorized, there were 36 possible combinations of surface, condition, and terrain; this test route had 13 out of those 36. The roadway width varied from 3 to 8 meters and our average segment speeds, from 23 to 45 km/hr. (There would be a tendency on the part of some estimators to use the poorest segment as a limit on capacity, thereby solving the variability problem and making a safe estimate from the standpoint of a U.S. transportation planner, but perhaps too low an estimate for intelligence purposes.)

Thus far I have raised quite a set of problems...let's review them with Chart 8. There are still many unexplored relationships. Even if we had established all of these, roads are variable and hard to describe precisely. Field test resources to take all of this into account are probably enormous. Even if we could cross these barriers, intelligence on roads is variable and generally presented in simple summary form. It follows that the methodology should be logical and realistic but it should be not much more sophisticated than warranted by the quality of intelligence data, at least when it is used for intelligence estimates. (For our own planning purposes we can get as sophisticated as we like.) This leads us to focus on the essentials and come up with a fairly simple method. Next we'll discuss some of the essential relationships in terms of the major factors involved.

SURFACE TYPE

It is common to categorize surfaces in terms of the material used. This is consistent with estimating long-term capacity because the more durable materials, depending on base thickness and subsoil, will change less under hard usage; the less durable materials will have their

condition degraded unless there is adequate road maintenance. These relationships should be preserved in the methodology.

Maximum speeds are reduced as the surface goes to a lower category, even though different surfaces may be in the same condition category. A good cobblestone road is simply not as fast a surface as a good paved road. This points up the fact that condition ratings are relative... they depend on a subjective comparison of the road being compared with the best possible road of that type of surface. Also, there can be overlap: a laterite road in good condition may be faster than a cobblestone road in poor condition.

Regardless of condition, metalled and natural surfaces generate dust unless they are moist. This is another important effect of surface type.

ROADWAY AND SHOULDER WIDTH

There are three obvious relationships here. First, if a road is so narrow that it can only be used for one-way military truck traffic, this has a significant effect on capacity (in our simplified method we estimated one-way truck rates as one fourth of two-way because of the extra time required to return empty trucks and to clear the road of trucks so that the direction of flow can be reversed). Second, if a road is quite narrow for either one-way or two-way traffic, there is some reduction of speed. At intermediate widths this effect is harder to determine. Studies of civilian traffic show no degradation of speed until the road becomes quite narrow; drivers simply took more risks and maintained speed.* Our field test gave similar results. Third, the effects of other traffic, road maintenance, and obstacles (such as disabled trucks) are definitely aggravated as roads and shoulders become narrower. During our test, roads that would have been one-way under military usage were used for two-way civilian traffic, which was relatively light, because the shoulders were used for passing (sometimes

* But used shoulders to some extent.

precariously). This would be a false assumption for military planning because shoulders are generally of inferior material and would soon break down. Their use for occasional stops and as a place to park construction equipment may be more acceptable.

TERRAIN

We are familiar with the sight of a heavy commercial truck crawling up or down a grade. We should remember, however, that military trucks are powered for cross-country operation and may have surplus power on conventional highway grades. Our Toyota $2\frac{1}{2}$ ton trucks in the field test were quite agile in mountainous country, even when fully loaded and pulling trailers. In making intelligence estimates of road capacity, truck type might interact strongly with terrain; for example, if the Communist Chinese make use of civilian trucks.

We were not able to test the concertina effect which occurs in rolling terrain, nor were we able to determine if convoy doctrine (extra spaces between groups of trucks) compensated for this effect. Further tests may show that terrain reduces capacity because of its effect on truck spacing. Another effect which had little impact on our test was that of sight distance, as reduced by curves and grades. Again, a steady stream of two-way truck traffic might amplify this effect. One interesting question about terrain is, given other conditions that are holding speed down and perhaps determining lead (such as surface, condition, and dust) does the additional limitation of terrain cause a further reduction in speed or capacity? We know that during our test there were times when we could have driven faster over roads in mountainous terrain if the surface had been smoother.

SURFACE CONDITION

This is an important determinant of speed and possibly of capacity. The main problem here is that of defining condition. We found, for example, that some roads that appeared to be in poor condition were faster than some that looked better, so we adjusted our descriptions accordingly. Again, truck type enters in because of the interaction

between a given surface profile and the truck's wheels and suspension system. One truck might pitch violently over a certain surface, thus limiting its speed, while another truck might have less trouble. (We found that we could make better speeds over some roads while loaded; also at night when the headlights gave the driver more advance notice of bad spots.) Even if one could define a road's condition precisely, perhaps by using a profilometer and categories of roughness (and this would hardly be feasible in hostile territory), the chances are that the condition would change with time, particularly if it were suddenly submitted to heavy usage. Factors such as surface type, base thickness, subsoil, moisture, drainage, elevation of the surface above flood level, previous usage, and road maintenance resources combine to have widely differing effects on condition. It is doubtful that we can make precise predictions for all combinations of these, but perhaps we can predict an approximate equilibrium condition for each of several levels of maintenance.

CONVOY DOCTRINE

The SOP established for truck operations may alter the capacity estimated for a set of physical characteristics. For example, here is the SOP for the Stilwell Road in 1945 (note that it does take some conditions into account):*

- "Speed Limits: (1) For winding, mountainous sections, 15 mph
(2) In flat, open sections, 25 mph
(3) Reduce speeds on dusty roads and muddy roads.
In general, road conditions will govern speed limits, with a maximum limit of 25 mph.

Close column type of march will be employed by all convoys in order to form a compact, well controlled column. Distance between vehicles will be twice the number of yards as the speed indicated on the speedometer. Infiltrating with convoys ahead is prohibited. Convoys will be divided into serials of approximately 25 vehicles, with either an officer or an experienced NCO bringing up the rear of each serial. Serials will travel from 15 minutes to 30 minutes apart."

*Source: SOP - Movement of Convoys, Ledo-Kunming, Over the Stilwell Road, HQ ADSEC 3, U.S. Forces in India-Burma Theater, 24 March 1945.

Doctrine may also regulate rest stops en route, establish operating and maintenance periods, and set rules for recovering or removing disabled vehicles.

LOC ESTIMATES

Thus far we have talked about estimating the capacities of individual road links. Going beyond this, we are often interested in lines of communication consisting of several, perhaps many, types of roads. Chart 9 shows how this is handled currently: the LOC from A to B has a capacity determined by its weakest link (shown in black). If B is an assumed enemy objective, we are given an estimate of the maximum and minimum short tons per day deliverable to B based on the weak link. For Southeast Asia, the maximum is generally for the dry season and the minimum for the wet season. In summary, estimates only the main route A-B would be shown; the other routes would be described as not contributing to capacity but available as alternate routes.

If the weak link is a one-way road, and this is frequently the case in Southeast Asia, the alternate routes should be taken more seriously. On the chart, for example, there is an alternate way of returning empty trucks to A; if this were used, it could increase the capacity of the LOC by a factor of four because the weak link would then have the forward capacity of a two-way road and no road time would be required for returning empty truck, and for convoy clearance (each of these requirements can cut a road's capacity in half). With a more complicated network and several sources and objectives one can use sophisticated analytical techniques to maximize the over-all flow through the network. This probably gets beyond the realities of military planning, but I think we should at least take into account the obvious possibilities for increasing capacity.

CONCLUSION

It is hoped that further field testing and analysis will result in a new method for estimating road capacity, a logical method which takes physical relationships into account when possible, coupled with

empirical factors derived from the tests. If we are only concerned with intelligence estimates of capacity, the method should not require information that would seldom be available. It may be possible, especially in tactical situations, to augment road data with aerial photography; accordingly, it would be useful to augment the field testing with experiments in interpreting aerial photography to confirm or improve capacity estimates.

BASIC FORMULAS

V = SPEED P = TRUCK RATE (TRKS FWD/HR)

d = LEAD T = TURNAROUND TIME

P = PAYLOAD N = NUMBER OF TRUCKS

p = OPER PD S = SUPPLY RATE (TONS FWD/DAY)

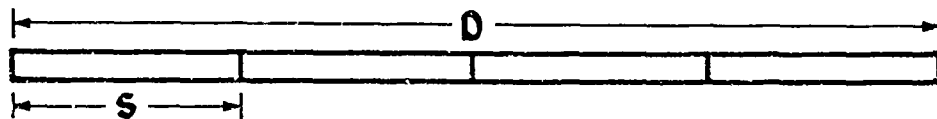
$$(1) \quad R = \frac{V}{d} \frac{\text{KM/HR}}{\text{KM/TRK}} = \frac{\text{TRKS}}{\text{HR}}$$

$$(2) \quad N = RT = R \frac{D}{V}$$

$$(3) \quad S = RP_p$$

Chart

ONE-WAY ROADS



$$a = \text{NUMBER OF SEGMENTS} = \frac{D}{s}$$

x = NUMBER OF ROUND TRIPS PER OPERATING PERIODS

HRS PER ROUND TRIP	HRS TO CLEAR CONVOY TWICE
-----------------------	------------------------------

$$(1) \quad n = \frac{V}{d} \left(\frac{p}{x} - \frac{2s}{V} \right)$$

$$(2) \quad N = na$$

$$(3) \quad S = nPx$$

ONE-WAY ROADS: EFFECT OF OPERATING PERIODS

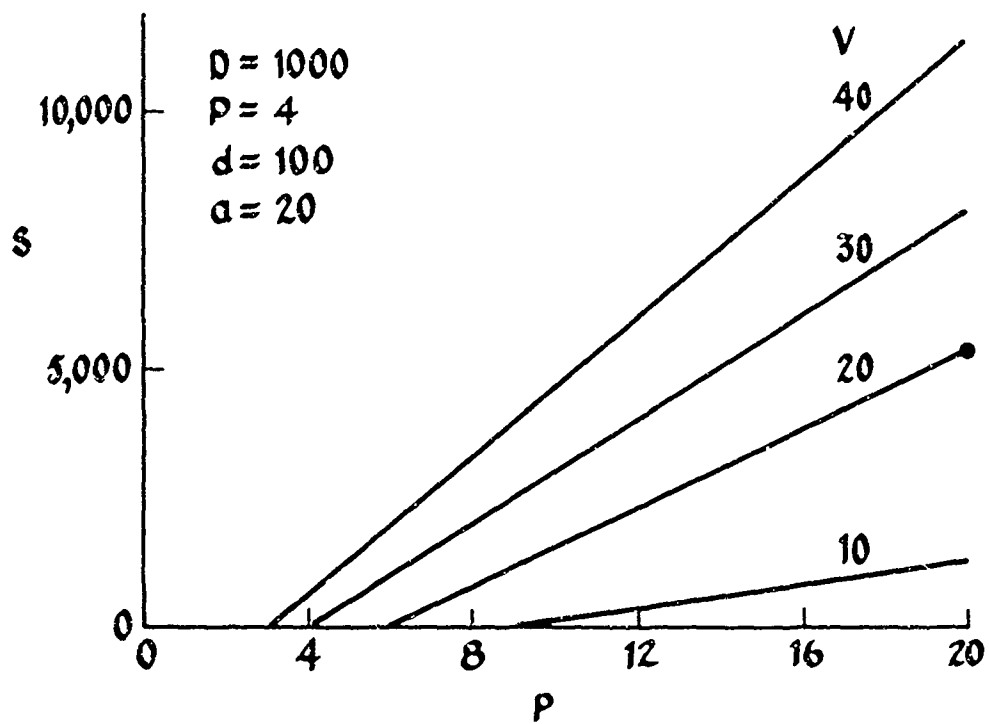


Chart 3

ONE-WAY ROADS: EFFECT OF SEGMENT LENGTH

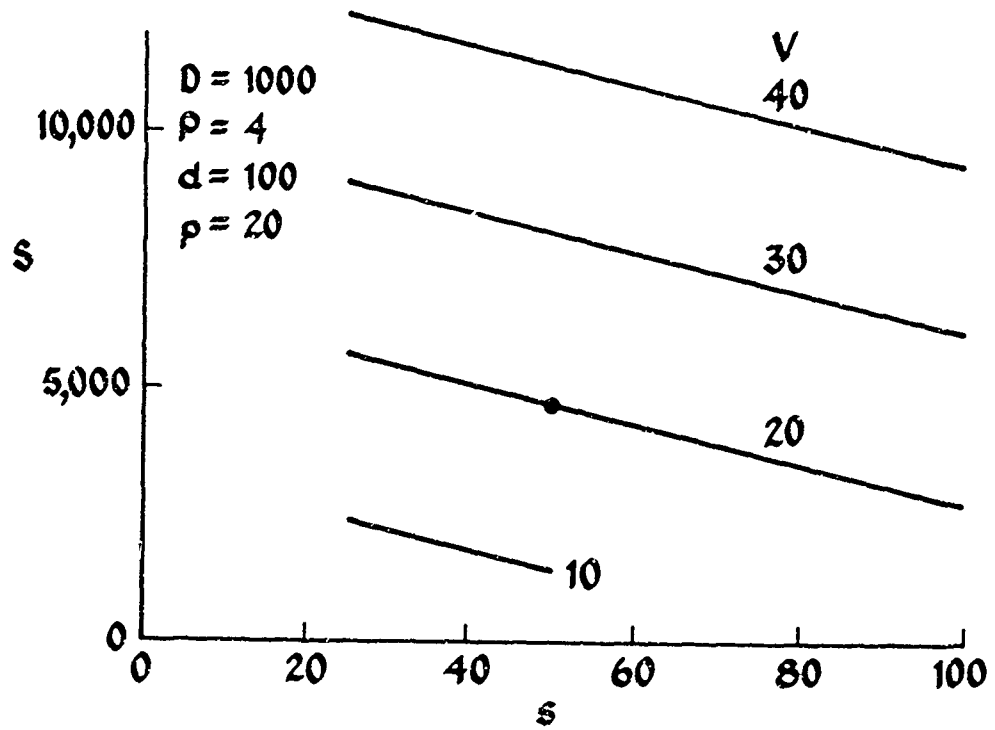


Chart 4

FACTORS INVOLVED

- SURFACE TYPE (4)*
 - BASE THICKNESS (3)*
 - SUBSOIL (3)*
 - CONDITION (3)*
 - ROAD MAINTENANCE
 - ROADWAY WIDTH (6)*
 - SHOULDER WIDTH (3)*
 - TERRAIN (4)*
 - MOISTURE (3)*
 - CONVOY DOCTRINE
 - TRUCK TYPE
 - GROSS WEIGHT LIMIT
 - OPERATING PERIOD
 - EN ROUTE STOPS
 - DRIVER SKILLS
 - DAY VS NIGHT
 - EMPTY VS LOADED
 - TRUCK MAINTENANCE
 - OTHER TRAFFIC
- *(29,160 COMBINATIONS)

INTERRELATIONSHIPS

	N	S	R	d	V	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 Surface type	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
2 Base thickness	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
3 Subsoil	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
4 Condition	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
5 Road maintenance	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
6 Roadway width	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
7 Shoulder width	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
8 Terrain	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
9 Moisture	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
10 Convoy doctrine	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
11 Truck type	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
12 Gross weight limit	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
13 Operating period	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
14 En route stops	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
15 Driver skills	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
16 Day vs. night	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
17 Empty vs. loaded	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
18 Truck maintenance	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
19 Other traffic	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

☐ Considered by RAND

EXAMPLE: KHORAT TO NONG LEE

DISTANCE 131 KM; SPEED RANGE 23-45 KM/HR

20 SEGMENTS IDENTIFIED; WIDTH RANGE 3-8 METERS

**SURFACES: BITUMINOUS, LATERITE,
COBBLESTONE**

CONDITIONS: POOR, FAIR, GOOD

**TERRAINS: FLAT, UNDULATING,
HILLY, MOUNTAINOUS**

13

**COMBINATIONS
OF 36 POSSIBLE**

PROBLEMS

- UNEXPLORED RELATIONSHIPS
- VARIABILITY OF ROADS
- RESOURCES REQUIRED FOR COMPLETE
FIELD TEST
- IMPERFECT INTELLIGENCE
- MATCHING METHODOLOGY TO
INTELLIGENCE

Chart 8

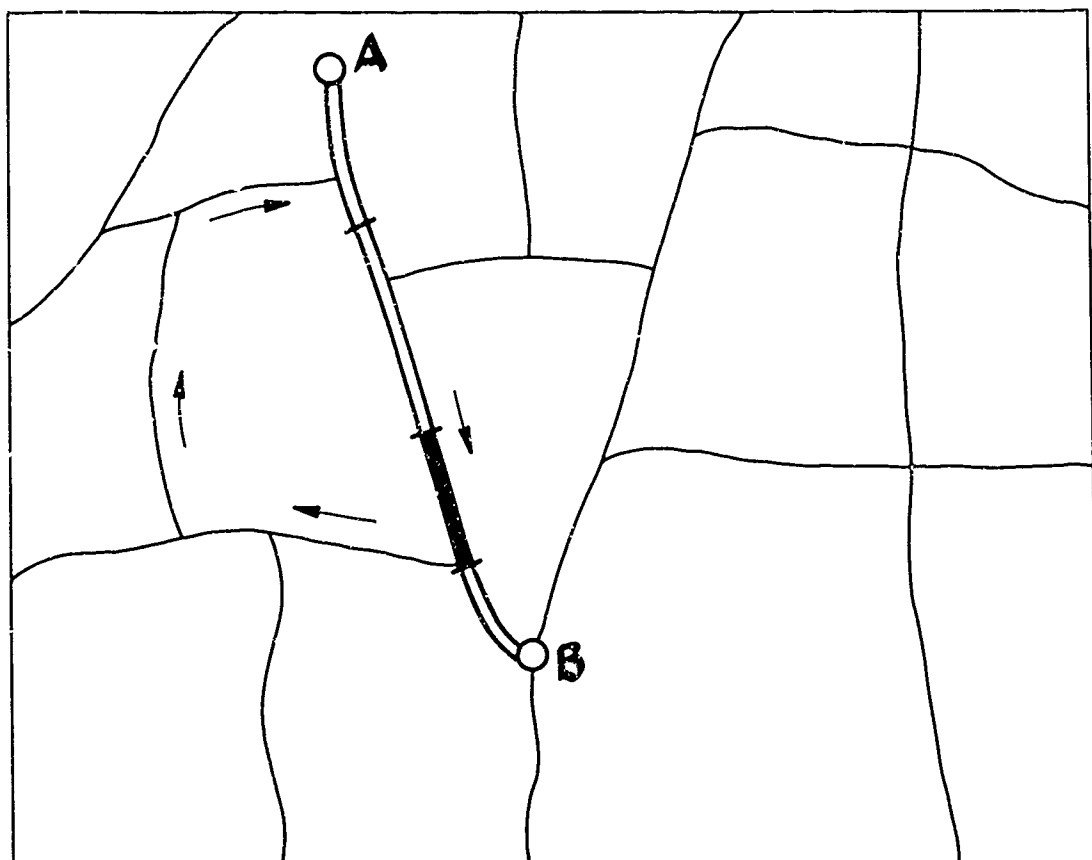


Chart 9